Chapter Four

Integrated Studies in the Water Column

4.1 Overview

The ocean is the primary realm removing anthropogenic CO_2 from the atmosphere, particularly on multidecadal to centennial timescales. Anthropogenic CO_2 enters the ocean at the surface but is rapidly mixed down into the thermocline. There it resides for many decades until it is gradually transferred to the deep ocean. Accurately characterizing the evolving inventory and distribution of anthropogenic and natural (total) CO_2 in the ocean interior is fundamental for several reasons. First, it gives basic information about the evolving disposition of anthropogenic CO_2 that is not remaining in the atmosphere. Second, the distribution of anthropogenic CO_2 in the ocean interior reflects the governing processes of surface uptake and redistribution by ocean circulation. The anthropogenic CO_2 distribution thus allows us to test and improve models of processes controlling ocean uptake, thereby improving our predictive capabilities. Third, the distribution of anthropogenic CO_2 reflects regional uptake rates of CO_2 at the sea surface and subsequent horizontal transports. In this way, the oceanic distribution of anthropogenic CO_2 gives an independent constraint on basin-scale ocean uptake and redistribution for comparison with air-sea flux estimates. These regional constraints on ocean uptake are also important for quantifying continental-scale CO_2 uptake. Fourth, secular climate change is projected to alter large-scale ocean circulation and marine biogeochemistry, leading to corresponding changes in the background natural ocean carbon cycle and the partitioning of carbon between the ocean and atmosphere.

We recommend three components to the program for ocean interior measurements.

1. A series of repeat ocean transects, involving reoccupation of selected meridional and zonal World Ocean Circulation Experiment (WOCE) lines, in which CO_2 system properties will be measured along with hydrographic properties, nutrients, and transient tracers.

2. Time series stations, including autonomous sampling from moorings, that provide data on monthly to seasonal timescales for measurement of hydrography, CO_2 properties, nutrients, and (at appropriate intervals) transient tracers.

3. Support for the development of autonomous platforms and instruments that measure properties of interest in the ocean interior, and for deployment as these capabilities become operational. Such equipment will allow us to greatly improve the spatial and temporal resolution of our measurements.

These efforts should provide important information on several essential subjects:

- The evolving distribution of both natural and anthropogenic CO_2 in the ocean interior. Meridional ocean sections, supplemented by zonal lines and time series, will give this information. The evolving time-dependent CO_2 distribution reflects the sum of oceanic processes and is therefore a first-order constraint on models used to predict ocean CO_2 uptake.

- Transport of CO_2 in the ocean interior. Zonal lines provide the primary constraints on meridional transport of natural and anthropogenic CO_2. Patterns of transport reflect processes of uptake and redistribution.

- Interannual and decadal variability in the oceanic distribution of CO_2 and bioactive tracers. There is evidence that oceanic ventilation and rates of biogeochemical processes vary during events such as the Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), and El Niño-Southern Oscillation (ENSO). Understanding these variations will allow us to document the influence of interannual and decadal variability on ocean uptake of fossil CO_2, and governing processes.

- Improved constraints on air-sea CO_2 fluxes. Interior ocean CO_2 fluxes depend, in part, on basin-scale uptake rates of anthropogenic CO_2. The data thus give a rate that can be compared with air-sea CO_2 fluxes measured by sea surface studies. They also give a critical independent constraint for inverse calculations of CO_2 uptake by the land biosphere.

- Improved constraints on ocean biogeochemical models. All the information listed in the items above is critical for the validation of ocean biogeochemical models used to predict future carbon distributions and fluxes.

Ocean interior studies should be a continuing effort that exploits strong linkages with the Climate Variability and Predicitability (CLIVAR) program and other complementary programs to make efficient use of ship time, moorings, and autonomous platforms.

4.2 Background

Two intertwined approaches have been used to constrain the current ocean uptake of anthropogenic CO_2 from the distribution of properties in the subsurface ocean. In the first approach, the composition of subsurface waters is used to calculate the concentration of anthropogenic CO_2 and its rate of increase. In the second, models describing the large-scale mixing and transport of the oceans are used to predict the present and future uptake rates of anthropogenic CO_2 and its oceanic distribution. In the past, the modeling approach has received the most attention. Models of increasing complexity have been used to calculate that the global oceanic uptake rate of anthropogenic CO_2 was about 2 Pg C/yr in the 1980s, rising to about 2.4 Pg C/yr at present (Orr *et al.*, 2001).

The other approach, estimating the large-scale anthropogenic CO_2 distribution from observations, is currently hampered by the lack of high-quality historical CO_2 data. We lack an adequate baseline to infer directly the change in CO_2 inventory over time. As a result, the (small) anthropogenic CO_2 concentration must be inferred using an estimate of its pre-anthropogenic value calculated from the modern concentrations of CO_2 and other properties. Chen and Millero (1978) and Brewer (1978) first outlined methods for this calculation; Gruber *et al.* (1996) have recently developed a modified approach. More recently, a number of alternative, albeit more indirect, means to estimate anthropogenic CO_2 have been proposed. These involve efforts to balance the global budget for ^{13}C of CO_2 (Heimann and Maier Reimer, 1996), or linking anthropogenic CO_2 to chlorofluorocarbons (Watanabe *et al.*, submitted, 2001; Gruber *et al.*, in preparation, 2001). All of these approaches require a global database of high-quality CO_2 measurements along with concentration data for other bioactive and hydrographic properties. The global CO_2 survey of the World Ocean Circulation Experiment/Joint Global Ocean Flux Program (WOCE/JGOFS) provided such a data set for the first time, making a major contribution to our understanding of ocean carbon uptake. These data, interpreted as described above, are yielding information about the oceanic distribution of anthropogenic CO_2 in the ocean, and basin- to global-scale inventories of these properties (Gruber *et al.*, 1996; Gruber, 1998; Feely *et al.*, 1999; Sabine *et al.*, 1999; Sabine *et al.*, 2001).

The reconstructed distribution of anthropogenic CO_2 in the oceans shows a strong surface- to deep-ocean gradient (Fig. 4-1). This is as expected for a tracer that invades the ocean from the surface; however, this surface- to deep-ocean gradient is not uniform. There are large differences between the North Atlantic, where anthropogenic CO_2 can be traced down to the bottom, and the tropical Pacific, where no anthropogenic CO_2 can be detected below 600 m. The highest concentrations and deepest penetration of anthropogenic CO_2 are associated with the Subtropical Convergence Zones. This distribution is consistent with that expected based on current knowledge of large-scale ocean circulation.

A second major finding evolving from the WOCE/JGOFS CO_2 survey is the success in reconstructing the change of inorganic carbon over time by comparing these high-quality data with historical data (Wallace, 1995; Slansky *et al.*, 1997; Peng *et al.*, 1998; Sabine *et al.*, 1999). Despite the lower quality of the historical data, the estimated changes over time are consistent with the trends expected based on the total anthropogenic CO_2 concentrations computed from the new hydrographic data alone. These results clearly demonstrate that the ingrowth of anthropogenic CO_2 can be observed by a repeat sampling of interior ocean water masses. The ingrowth of anthropogenic CO_2 over time has also been directly observed in mixed layer samples at the Bermuda and Hawaii long-term observations sites (Winn *et al.*, 1996; Bates, 2001).

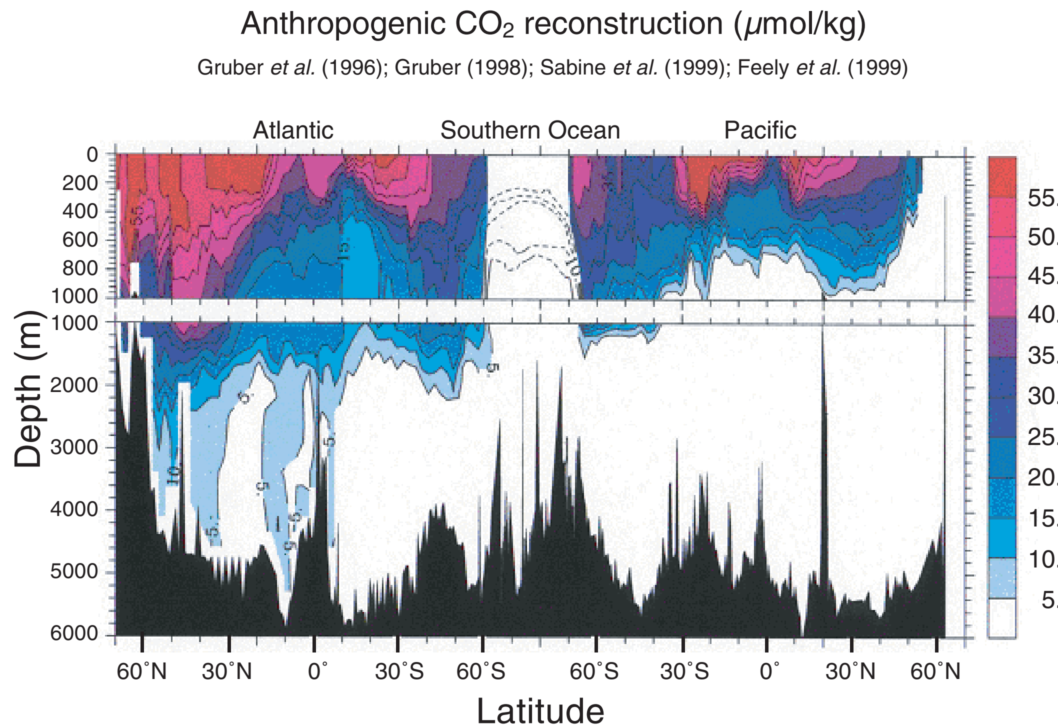

Figure 4-1: Distribution of anthropogenic CO_2 in the Atlantic and Pacific Oceans (after Gruber *et al.*, 2000).

The main factor controlling the current uptake of anthropogenic CO_2 by the ocean is the transport of this "excess" CO_2 from the surface into the interior of the ocean. Other anthropogenic tracers that follow the same pathway of ocean uptake provide powerful constraints on the oceanic CO_2 uptake. Such anthropogenic tracers include bomb radiocarbon and anthropogenic halocarbons. Their advantage over anthropogenic CO_2 is that they are entirely anthropogenic, or their natural abundance is at least better known. These tracers, together with estimates of the oceanic distribution of anthropogenic CO_2 and its rate of change, therefore, provide a critical target/test for ocean circulation models. The models do a good job of simulating the global ocean inventory of anthropogenic CO_2 (Orr *et al.*, 2001). However, they are less successful in computing regional distributions of anthropogenic CO_2 and other tracers in the oceans (Fig. 4-2; Gruber, 1998; Orr *et al.*, 2001; Dutay *et al.* 2001).

The discrepancies between data on transient tracer distributions and model predictions highlight ways in which the models can be improved. For example, recent intercomparisons of model output have allowed diagnosis of model characteristics that lead to divergent predictions (`http://www.ipsl.jussieu.fr/ocmip/`). These comparisons, and ongoing model improvements, will lead toward two advances in our understanding of the oceanic uptake of anthropogenic CO_2. Improved models will allow for more accurate interpolations of oceanic concentration fields, thereby giving well-constrained basin- and global-scale CO_2 inventories with sparser data sets. Further, more

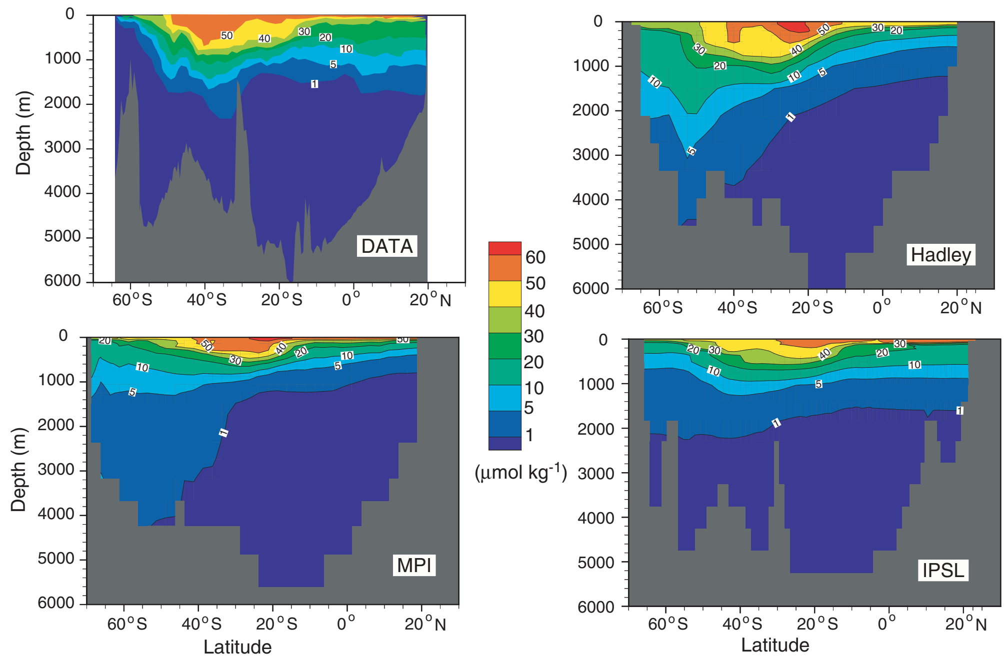

Figure 4-2: North-south section of anthropogenic CO_2 (μmol/kg) in the Indian Ocean at 92°E from observations (DATA) and from simulations by OCMIP models. Model abbreviations are: MPI = Max Planck Institüt für Meteorologie—Hamburg, Germany; Hadley = Hadley Centre for Climate Prediction and Research, Bracknell, England, UK; IPSL = Institute Pierre Simon LaPlace, France.

accurate models will lead to improved projections of ocean uptake rates of CO_2, and hence better predictions of the evolution of atmospheric CO_2 burdens.

Improvements in observations and modeling of ocean ventilation are essential components of a carbon-observing plan. To first order, the long-term oceanic uptake of anthropogenic CO_2 is regulated by water mass transport. In planning a decadal-scale observing program, a better understanding of carbon transport within the ocean's interior can help identify critical areas that need additional sampling and monitoring for those changes in overturning that may have serious consequences for future anthropogenic uptake. Preliminary efforts to compute the regional and basin-scale horizontal carbon transport within the ocean using hydrographic sections and inverse techniques have been very promising. For example, Holfort *et al.* (1998) used data from three WOCE/JGOFS sections together with several pre-WOCE cruises in the South Atlantic between 10°S and 30°S to estimate meridional carbon transports in this region. Notable findings by Holfort and colleagues are that the net preindustrial carbon transport across 20°S was toward the south, but the net anthropogenic CO_2 transport is toward the north. This occurs because anthropogenic carbon is generally restricted to the upper, northward-moving waters and the southward-moving North Atlantic Deep Water has not yet been contaminated by the anthropogenic signal at this latitude. A study of ocean transport links the carbon flux es-

Table 4-1: Existing time-series stations in the oceans.

Existing time-series stations	Autonomous sensors	CO_2	Transient tracers
S/BATS/BTM, Bermuda/U.S.	yes	yes	no
HOT, Hawaii, U.S.	no	yes	no
Eq. Pacific, especially 0°, 155°W, 2°S, 170°W, U.S.	yes	yes	no
Station Papa, NE Pacific, Canada	no	yes	no
Mike, Norwegian Sea, Norway	no	no	no
KNOT, NW Pacific, Japan	no	yes	no
ESTOC, Canary Islands, Spain/Germany	no	yes	no
Bravo, Labrador Sea, Canada	no	no	no

timates provided by the surface observation program and the ocean storage derived from the ocean interior work proposed here. The "natural" transport of oceanic carbon is a key constraint for modeling and interpreting the meridional atmospheric gradients. By studying the transports from "boxes" bound by high-quality observations, the divergences in natural and anthropogenic CO_2 can also be used to pinpoint the long-term sources and sinks of CO_2. Thus, observations and transport calculations provide an independent check on the uptake estimates from models and observations of air-sea CO_2 fluxes.

As previously described in detail in Chapter 3, time-series studies within the oceans are required to delineate the interannual and decadal variability caused by long-term changes in ocean circulation and biology that occur in response to the penetration of anthropogenic temperature and CO_2 signals into the oceans. Time-series studies are similarly needed to assess the variability that is the result of natural climatic changes including ENSO, PDO, NAO, etc. At present, there are only a few places where long-term observations allow us to assess the magnitude of interannual variability (Table 4-1), prominent examples being the JGOFS studies at the Hawaiian Ocean Time-series site (HOT; e.g., Karl and Lukas, 1996; Karl, 1999) and Bermuda Atlantic Time-series Study site (BATS; e.g., Steinberg *et al.*, 2000; Bates, 2001). This important work has shown that variability is as much an implicit component of the ocean carbon cycle as it is of climate in general (Karl *et al.*, 2001).

From observations at the HOT site over the past three decades, Karl and coworkers (Karl, 1999; Karl *et al.*, 2001) have observed systematic changes in the community structure of phytoplankton that have been linked to phase changes in the Pacific Decadal Oscillation. They suggested that large-scale changes in the stability of the water column caused systematic shifts in the phytoplankton community leading to enhanced nitrogen fixation. Such changes can have profound impacts on the net exchange of carbon between the upper ocean and the ocean interior because nitrogen fixation will lead to increased export from the euphotic zone into the permanent thermocline. It also might impact the air-sea balance of CO_2 indirectly in that such a community structure change can lead to a net increase of the available fixed nitrogen for general phytoplankton growth and export.

Studies at BATS have also demonstrated interannual to decadal variability in ecosystem responses to physical forcing and upper ocean biogeochemistry that may be linked to large-scale processes of ocean variability. Bates (2001) and Gruber *et al.* (in preparation, 2001) showed, for example, that biological production and air-sea fluxes of CO_2 are strongly correlated with sea-surface temperature variations, which are themselves to a significant degree controlled by interannual to decadal variations in the North Atlantic Oscillation. These changes not only manifest themselves in the upper ocean, but often show up even more strongly in the thermocline (Bates, 2001; Joyce and Robbins, 1996). The BATS results clearly show significant increases in interior ocean TCO_2 concentrations over time in subtropical mode waters ($\sim$2.3 μmol kg/yr) that may be related to changes in atmospheric conditions over the North Atlantic resulting in changes in water column ventilation processes (Bates *et al.*, 1996). Similar changes may be occurring elsewhere in the intermediate waters of the oceans.

Research from other long-term time-series programs such as the California Cooperative Fisheries Investigation (CalCOFI) (Roemmich and McGowan, 1995) and from Ocean Weather Station Papa (Takahashi *et al.*, 1993, 1997) all show that the view of a static ocean is mostly a result of the absence of oceanic data to document upper ocean ecosystem changes and that variability cannot be neglected. Interannual variations recorded at the few time-series stations are hardly local phenomenon. Rather, large-scale changes in the climate system affect the distribution of carbon and other bioactive tracers in a major way. An illustration comes from the recent finding that the thermocline oxygen content changed throughout the North Pacific basin in recent decades (Pahlow and Riebesell, 2000; Keller *et al.* 2001; Emerson *et al.*, in press; Watanabe *et al.*, submitted, 2001). These authors have analyzed hydrographic data in the North Pacific and discerned evidence for changes in nutrient and O_2 inventories in thermocline waters as well as the shallower waters of the deep ocean. The variations must be caused by changes in biogeochemical fluxes or by variations in ventilation rates. At present we cannot determine which. Either cause would have an effect on the net transfer of CO_2 across the air-sea interface and therefore directly on the ocean uptake rates of anthropogenic CO_2. We also do not know whether the biogeochemical changes are natural or are harbingers of future global climate change. The latter was interpreted as the reason for large-scale oxygen changes in the Southern Ocean (Matear *et al.*, 2000).

Global change simulations have examined the implications of global warming for the uptake of anthropogenic CO_2 during the coming century and beyond. A consistent finding in these studies is that warming and increased precipitation induce increased stratification, most notably in the Southern Ocean (Sarmiento *et al.*, 1998; Matear *et al.*, 1999). Increased stratification, in turn, has two counterbalancing effects on upper ocean biogeochemistry. The first is a reduction of upwelling and productivity, particularly in the low latitudes; the second is an increase in nutrient utilization (Bopp *et al.*, 2001). The Southern Ocean has a particularly large potential to modulate anthropogenic CO_2 uptake because of its large nutrient reservoir. In agreement with this expectation, modeling studies point to the Southern Ocean as the critical region in which ocean change can cause large changes in anthropogenic CO_2 uptake (Sarmiento *et al.*, 1998; Matear *et al.*, 1999).

Understanding interannual to decadal variability linked to ocean ventilation is important for two reasons. First, the response of ocean chemistry and biogeochemistry to variability in the physical forcing gives mechanistic insight that can ultimately be expressed in predictive models. Second, global change may induce switches in ocean physics that are extensions of natural variability. One example is the possibility that the eastern tropical Pacific may become more El Niño-like as Earth warms, with corresponding increases in seawater temperature and reduced CO_2 distributions (McPhaden, 1999; Feely *et al.*, 2001). Thus, variability now expressed over decadal timescales may foreshadow century timescale evolution in the era of global change. Characterizing interannual variability is a major focus of our recommendations. Long-term continuous observations are critical in this respect.

This chapter recommends two approaches for the study of CO_2 in the ocean interior. The first involves periodic hydrographic studies to map out the long-term increase in the oceanic burden of anthropogenic CO_2 and other transient tracers. This work will also document snapshot variability in oceanic distributions of bioactive tracers reflecting decadal variability in carbon fluxes and ventilation rates. The second approach involves ongoing observations of bioactive tracers (and related properties) at time series stations where oceanic variability is likely to be manifested.

The program has several overarching objectives:

- Determine the large-scale decadal evolution of the anthropogenic CO_2 inventory to within 10% ($\sim$3 Pg C globally over the next decade) on a global and basin scale.
- Close the decadal basin-scale budget of carbon to within 0.1 Pg C/yr on the basis of inventory changes, lateral transport, and air-sea flux.
- Determine the response of the oceanic carbon system to interannual and interdecadal climate variability.
- Provide decadal time-scale changes in the distribution of CO_2 species, transient tracers, and other biogeochemical tracers to constrain models to improve their predictability.

Our stated objective is to determine the anthropogenic CO_2 burden of ocean interior waters to $\pm$3 Pg C. A daunting challenge comes from the fact that the total oceanic CO_2 inventory is about 12,000 times larger than this anthropogenic contribution (38,000 Pg C). The average concentration increase over the entire global oceans would be approximately 0.2 μmol/kg, at least 5 times less than the present analytical uncertainty. What makes this objective tractable is that decadal CO_2 invasion is concentrated almost entirely in the upper 10% or less of the oceans, which makes it possible to accurately constrain the changing inventory of these waters. Observations of CO_2 cannot address the possibility that underlying waters are repositories for small amounts of anthropogenic CO_2 that, in aggregate, comprise a significant part of the balance. We recognize this possibility and believe that it should be addressed, to the extent possible, by measuring the abundance of halocarbons and other diagnostic tracers. However, we focus in our discussion on quantifying anthropogenic CO_2 inventories of shallower waters, which, we believe, dominate the mass balance.

An important constraint on the sampling system is that key variables must be measured over appropriate time and space scales. We are learning that the entire spectrum of dynamic processes in the oceans, ranging from episodic processes (hurricanes, mesoscale eddies, etc.) to basin-scale climatic changes (ENSO, PDO, NAO, etc.) are important, so complete reliance on infrequent ship-based observations is not an option (Dickey, 2001). Thus, the strategy is to put in place a global ocean-observing network of sampling platforms to provide observations in the form of repeat ship-based sections, time-series stations, moorings, gliders, and profiling floats, to document the continuing evolution of these fields in time and space. These basin-scale measurements, along with integrative models, encompassing the Atlantic, Pacific, Southern, and Indian Oceans will constrain the evolving uptake rates of anthropogenic CO_2 by the oceans, independent of atmospheric and sea surface measurements. The data on anthropogenic CO_2 and other transient tracers will provide critical targets for ocean circulation models and the basis for ocean inverse/data assimilation efforts. Finally, the results will provide improved constraints on the atmospheric inverse models used to calculate fossil fuel CO_2 sequestration rates by North America and other continental land masses.

4.2.1 Network design

To the extent possible, we should use objective criteria to determine the scope of the network for repeat ocean sections and to design the network. Therefore, two of us (C. Sabine and R. Feely) conducted a network design study to test a strategy for constraining the uptake rate and distribution of CO_2 from hydrographic data. For this study three-dimensional global anthropogenic CO_2 fields from the NCAR OCMIP-2 Model (1.8° by 3.6° by 25 levels) were examined for model years 1995 and 2005. First, the 1995 model fields were linearly interpolated onto a $1° \times 1°$ grid and subsampled at the WOCE/JGOFS station locations. The subsampled values were then mapped back to the full basin for each level using a loess interpolation function. Integrating the maps over the appropriate volumes, basin-wide inventories were determined. These inventories agreed very well (within 0.1 Pg C) with the inventories determined by summing up all of the boxes in the full ocean model. This agreement indicates that the WOCE/JGOFS sampling density was sufficient to adequately constrain the full basin inventories in the major oceans.

Can ocean inventories of anthropogenic CO_2 be accurately constrained with surveys coarser in scale than those of WOCE/JGOFS? If so, how many sections are necessary? At least two possible approaches can be considered to cover the extremes. The first approach assumes that ocean circulation and biological activity on the basin to global scale has and will continue to operate at steady state. Anthropogenic uptake, under this approach, is based solely on the solubility pump. In this case, it might be possible to scale up the WOCE/JGOFS basin-wide inventories by resampling a few lines at a future date, deriving a function that describes the change in anthropogenic CO_2 along these lines, and using that function to estimate the new anthropogenic CO_2 concentrations from all of the original WOCE/JGOFS survey lines.

To investigate the feasibility of this approach, the changes in the NCAR anthropogenic CO_2 concentrations between model year 1995 and 2005 were compared with the 1995 concentrations. All of the model-based changes (for all depths and all oceans) fell along a single line showing a clear positive correlation with the 1995 concentrations. If these results held for the real ocean, it would imply that a single profile covering a range of anthropogenic CO_2 concentrations could be used to derive a function to scale up the WOCE/JGOFS data in the future. Unfortunately, the data do not appear to validate such an approach: anthropogenic CO_2 estimates for WOCE samples from the Indian Ocean do not vary linearly with estimates for GEOSECS samples of the same water mass. Therefore, we cannot expect to accurately constrain anthropogenic CO_2 inventories with a minimalist strategy involving simple scaling.

Ideally, the full WOCE/JGOFS survey should be repeated every decade, but the required resources are unlikely to be available. Therefore, we investigated the accuracy of inventories determined via intermediate sampling strategies using a second approach. Specifically, we subsampled anthropogenic CO_2 concentrations computed by the NCAR 2005 simulation. First, we examined inventories determined by running one zonal section through the center of each ocean basin. This second approach was tested for the Pacific by subsampling the NCAR 2005 model results along one N-S line and one E-W line. The interpolated basin-wide inventory for this limited data set generally agrees with the model inventory (60 vs. 65 Pg C). However, the regional distribution, calculated by loess interpolation, is very different. In fact, the anthropogenic CO_2 distribution is better reproduced by neglecting the zonal line and assuming that the meridional line represents constant zonal values. This interpolation approach gave a Pacific inventory of 63 Pg C (model = 65 Pg C). Differences between model inventories and zonal interpolation estimates were typically from 5 to 20 mol/m^2 (Fig. 4-3).

The largest differences were off the coast of North and South America and off Japan, where significant zonal gradients exist. The NCAR 2005 model was also subsampled using a sampling plan similar to that proposed by CLIVAR (Gould and Toole, 1999). This plan involves sampling about 4 to 11 lines per basin. The interpolated Pacific inventory based on four zonal lines and seven meridional lines was again approximately 63 Pg C, which is within our goal of 10%. Differences between the model and interpolated inventories were generally less than 5 mol/m^2. Zonal lines (with high resolution in the western boundary currents) are also critical in order to compute ocean horizontal transport. A few scenarios were tested where an additional zonal or meridional line was added, with very little effect on the final inventory. Similar studies were carried out for the other ocean basins with the same general results. Based on these findings, the proposed repeat section plan is

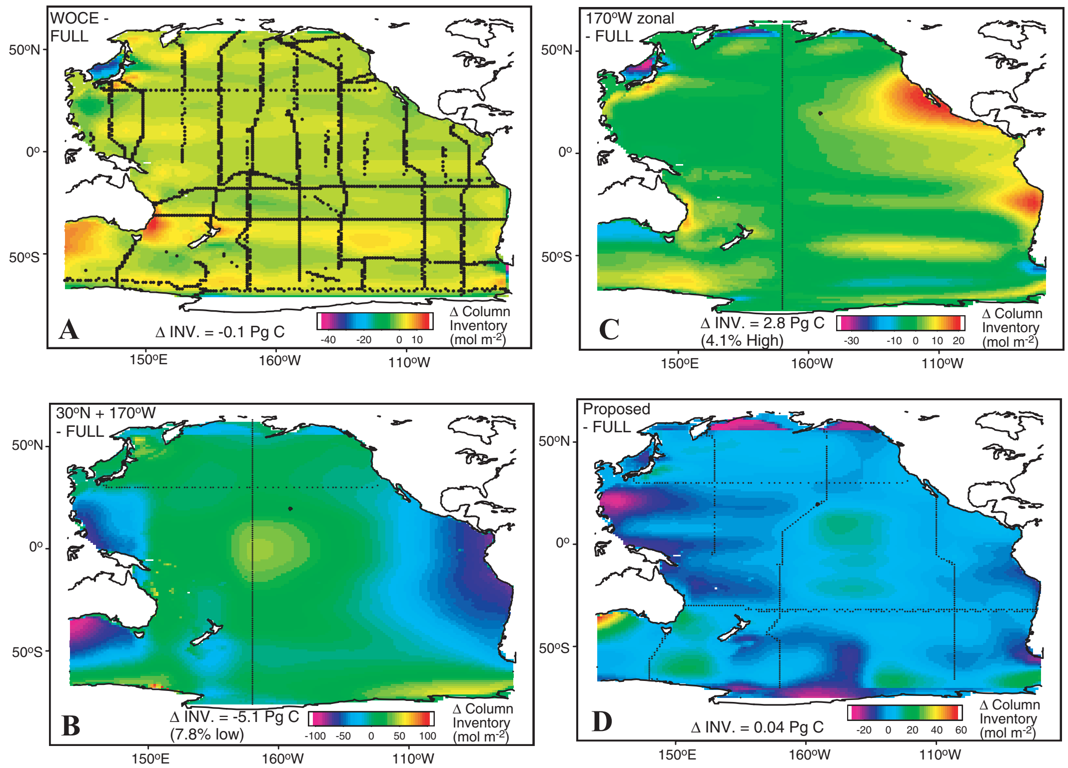

Figure 4-3: Maps of the difference between the Pacific anthropogenic CO_2, (A) column inventory from the NCAR model and the inventory determined by mapping the model values subsampled along the WOCE survey lines, (B) along one zonal and one meridonal section, (C) along one meridonal section assuming these values represent the zonal mean, (D) and along the repeat lines proposed in this document. Black dots on each map indicate sample locations. Note: color scales are different for each map.

likely to provide sufficiently accurate anthropogenic CO_2 inventories while requiring far fewer resources than the WOCE/JGOFS study (Fig. 4-4).

The difference between sampling along WOCE transects and sampling one meridional line per basin is simply that the former gives accurate information about distributions as well as inventories. We believe this distribution information is essential for three purposes: achieving confidence in inventories, understanding controls on anthropogenic CO_2 uptake and its distribution, and predicting future uptake rates.

Other countries are now committed to sampling some of the proposed CO_2 repeat transects. Interpolation of just the currently committed transects resulted in regional errors that were much larger than the full survey. Interpolation of only the U.S. transects proposed in this document also resulted in regional errors that were roughly twice the full survey errors. The best plan, of course, is a coordination and synthesis of repeat lines by the international community.

The results from this preliminary study depend somewhat on the distributions determined by the model as well as the choice of interpolation schemes. For example, the model is integrated with a repeat annual surface forcing, thus greatly reducing interannual to decadal variability. How the

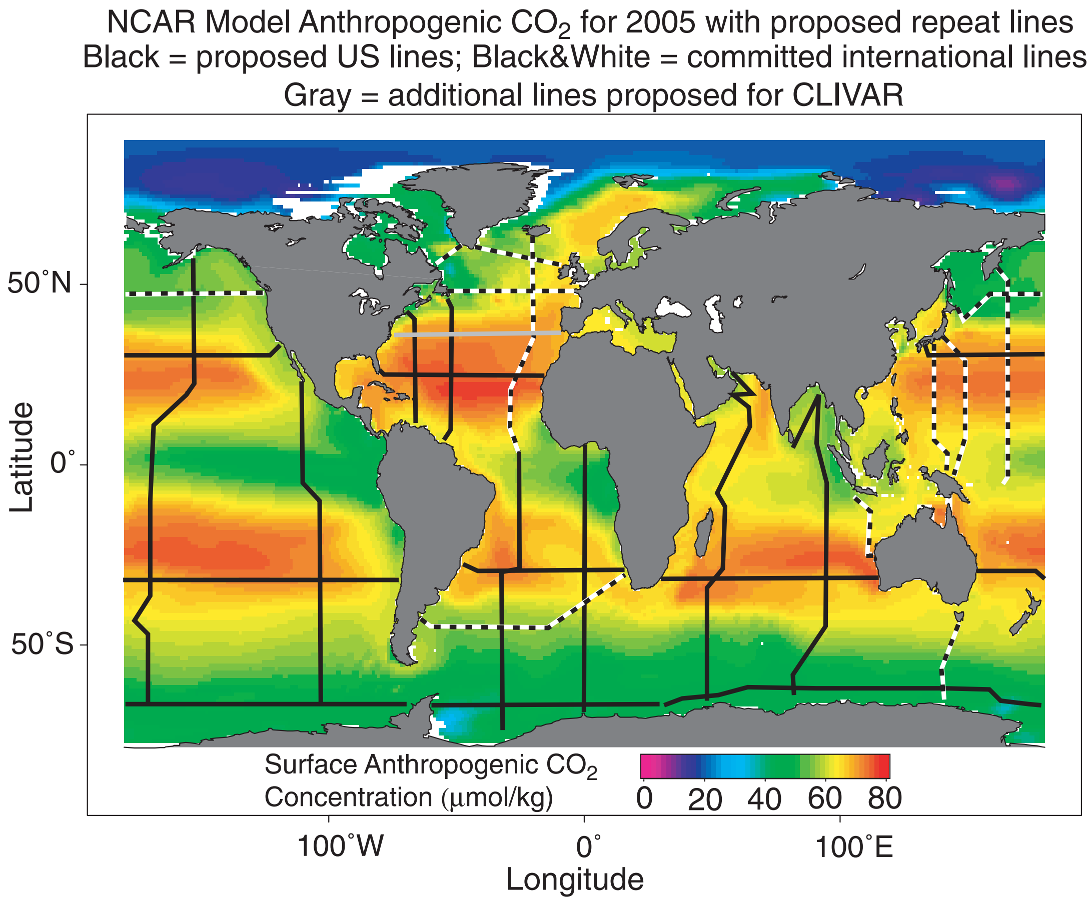

Figure 4-4: Locations of proposed repeat sections (black lines) for studies of circulation, transport anthropogenic CO_2 inventories. The grey lines are additional proposed CLIVAR cruise tracks and the black-and-white lines are committed repeat cruise tracks by similar international programs.

ocean will respond exactly to future changes in atmospheric CO_2 levels and climate change is also difficult to determine. The two scenarios examined here represent two end members: (1) steady-state circulation and biology and (2) a total redistribution of carbon, requiring a blind interpolation approach. The reality will likely be somewhere between these two extremes, suggesting that a conservative (oversampling) network design is prudent.

Even if the ocean circulation changes, the differences between two sequential 10-year repeat surveys will likely be restricted to the upper few hundred meters, where the thermocline waters are generally less than 10 years old. Thus, it is extremely unlikely that we will miss dramatic shifts in the ocean distribution of anthropogenic CO_2. The sampling strategy proposed in this document attempts to maximize the scientific return on resources, while maintaining the ability to detect and address potential surprises in the response of the ocean circulation and biology to future forcing.

4.3 Recommendations

We recommend as part of the ocean interior component of the plan two complementary and synergistic activities: large-scale repeat ocean sections, and time-series observations at fixed locations.

4.3.1 Repeat ocean sections

We recommend an ongoing program in which 15 repeat sections spanning the global ocean are resampled every 10 years. Properties to be measured include hydrography, redundant CO_2 system properties, nutrients, halocarbons, and emerging tracers of biology and physics.

We recommend that a subset of WOCE transects, shown in Fig. 4-4 and listed in Table 4-2, be reoccupied periodically for hydrographic and chemical studies. Our recommendations are formulated with the objective of characterizing the evolving ocean inventory of anthropogenic CO_2 among other properties. The recommended cruise tracks are based, in part, on the network design study described in the CLIVAR documents (Gould and Toole, 1999). We recommend that a modified version of their plan be adopted for characterizing the oceanic distribution of anthropogenic CO_2. Table 4-2 summarizes the objectives each cruise track will fulfill beyond the basic goal of mapping the transients and constraining the anthropogenic inventory. We recommend that each section be sampled from coast to coast. Such sampling is particularly important for zonal sections, which will be used for meridional transport calculations (Wunsch, 1996).

The requirements for ocean transport calculations should not add much of a burden to the repeat section work proposed here. Station spacing on the proposed sections should be 30 to 60 nautical miles to minimize aliasing by eddies and other mesoscale variability. The number of transects required to constrain the major oceans is estimated to be at least 2 to 4 meridional and 2 or 3 zonal sections per ocean (Taft *et al.*, 1995). Meridional sections are important for understanding variations in basin-scale circulation patterns and inventory changes. Repeat occupation of zonal sections allows for the detection of variability in the rates, pathways, and properties of deep and intermediate waters carried toward the equator from the high latitudes, and for detection of zonal variations in carbon storage. Attention must be given to potential biases resulting from seasonal variability in the transport. As a result, an intense period of seasonal sampling may be required to evaluate this issue. Ideally, the cruises should be coast to coast, located downstream of the deep and intermediate water formation regions. The required parameters are the same as those proposed to determine the inventory estimates. The transient tracers play a key role in the transport fluxes because they provide temporal information about ocean mixing and advection that is essential to interpreting anthropogenic CO_2 distributions.

Connections with climate programs such as CLIVAR are important for the success of the transport calculations. The repeat hydrographic survey transects proposed for CLIVAR are consistent with the requirements for the carbon measurement program outlined here (Gould and Toole, 1999;

Table 4-2: Suggested sections for whole water column hydrographic and tracer monitoring by the United States.

Atlantic Ocean	
24°N	Heat, freshwater and carbon/tracer fluxes/inventories
30°S	Heat, freshwater and carbon/tracer fluxes/inventories
52°W	Carbon/tracer invasion and transport in western gyre of N. Atlantic
66°W	Carbon/tracer invasion and transport in western gyre of N. Atlantic
0°	Carbon/tracer invasion and transport in eastern gyre of S. Atlantic
20–30°W	Carbon/tracer invasion and transport in western basin of S. Atlantic
67°S	Carbon/tracer invasion in the Southern Ocean
Pacific Ocean	
30°N	Heat, freshwater and carbon/tracer fluxes/inventories
32°S	Heat, freshwater and carbon/tracer fluxes/inventories
150–170°W	Carbon/tracer invasion and transport in eastern basin of N. Pacific, western basin of S. Pacific
105–110°W	Equatorial upwelling region and carbon/tracer invasion and transport in eastern basin of S. Pacific
67°S	Carbon/tracer invasion in the Southern Ocean
Indian Ocean	
55–65°E	Carbon/tracer invasion and transport in western basins of Indian Ocean; also choke point line south of Kerguelen
90°E	Carbon/tracer invasion and transport in eastern basins of Indian Ocean; also choke point line south of Broken Plateau
65°S	Carbon/tracer invasion in the Southern Ocean

Rintoul *et al.*, 1999). Potential benefits of a cooperative program include improved knowledge of the rate of change of heat and freshwater storage and fluxes. These can be directly related to carbon transports, linkages to CLIVAR-derived estimates of direct velocities (e.g., western boundary current moorings, floats, cables) required for transport calculations, and an assessment of changes in deep and shallow water-mass formation and overturning.

4.3.2 Properties to be analyzed on repeat sections

We recommend that samples be analyzed for a broad suite of hydrographic and chemical properties that are diagnostic of carbon inventories and fluxes. These can be divided into the following overlapping groups.

- Hydrographic properties (T and S)
- Major bioactive tracers (nutrients, O_2, TCO_2—total CO_2, TA—total alkalinity, pCO_2, DOC—dissolved organic carbon, DON—dissolved organic nitrogen, $\delta^{13}C$ of CO_2, and (at less frequent spacing/intervals) iron
- Transient tracers of ocean circulation (halocarbons, ^{14}C)

- Emerging tracers of mixing, biogeochemical processes, and deep water formation

These measurements will contribute in several ways. TCO_2, TA, nutrients, O_2, and halocarbons form the basic data set required for mapping the distribution of anthropogenic CO_2 in the oceans (e.g., Gruber *et al.*, 1996; Gruber, 1998; Feely *et al.*, 1999; Sabine *et al.*, 1999). Macronutrients (nitrate, phosphate, silicate) and micronutrients (e.g., iron) control the patterns and rates of ocean biogeochemistry and are sensitive indicators of climate change; iron is now thought to play a key role in limiting surface production in high-nitrate low-chlorophyll (HNLC) regions, but the oceanic distribution and budget is poorly characterized (Fung *et al.*, 2000). The balance of the global budget for ^{13}C of CO_2 between the atmosphere, oceans, and terrestrial biosphere provides an independent estimate of anthropogenic CO_2 uptake in the oceans, giving complementary information about its distribution (Quay *et al.* 1992; Tans *et al.*, 1993; Gruber and Keeling, 2001). DOC and DON are significant components the ocean carbon and nitrogen cycles because they make up approximately 20% of the global annual export flux to the interior ocean (Hansell and Carlson, 1988). At depth, the exported DOC is remineralized to CO_2, thus contributing to the CO_2 gradient created by the biological pump. We need to know the DOC and DON distributions in order to close the mass balance when calculating meridional fluxes from zonal sections.

The distribution of bioactive tracers serves to reflect both natural variations and anthropogenic changes in ocean ventilation rates and biogeochemical fluxes. Several studies have demonstrated variability in nutrient and O_2 concentrations of mode waters and thermocline waters linked to interannual hydrographic variability. For example, Bates (2001) and Gruber *et al.* (in preparation) demonstrated variability near Bermuda associated with the North Atlantic Oscillation. Karl *et al.* (2001) showed that the Pacific Decadal Oscillation induces significant variations in hydrography and nutrient properties, which may lead to long-term changes in the export flux of carbon. Several recent studies have demonstrated changes in North Pacific O_2 and nutrient concentrations of undocumented origin (Pahlow and Riebesell, 2000; Keller *et al.*, 2001; Emerson *et al.*, in press). Matear *et al.* (2000) predicted a large change in the ventilation of Southern Ocean waters, and argued that a comparison of O_2 concentrations measured in Eltanin and WOCE samples confirmed their model prediction.

Finally, calculations using the O_2 inventory of air to constrain anthropogenic CO_2 uptake by the oceans and land biosphere (e.g., Keeling and Shertz, 1992) require an assumption about the stability of the ocean O_2 inventory. Papers to date assume constancy. However work (cited above) showing variability in the O_2 concentration of thermocline waters challenges this assumption, suggesting that ocean changes may be quantitatively important. Measurements of O_2 concentrations in repeat ocean sections will give firm constraints on ocean O_2 inventory changes. They will allow one to use O_2 data to provide an independent estimate of ocean CO_2 uptake.

4.3.3 Transient tracers

Seawater distributions of anthropogenic chemicals constrain rates of oceanic mixing processes that influence the oceanic distribution of anthropogenic CO_2. Properties of interest include halocarbons, ^{14}C, $\delta^{13}C$ of CO_2, and anthropogenic CO_2 itself. Mapping the evolving distribution of these tracers provides unique and important information about ocean circulation. A noteworthy characteristic of transient tracers is that emission curves differ and, of particular interest, emissions of different chemicals begin at different times. Thus the periodic introduction of new chemicals effectively leads to repeat "dye experiments" which record changes in ocean circulation.

4.3.4 Emerging tracers of mixing and biogeochemistry

We are currently developing analytical methods and conceptual insights for new tracers that are important for understanding biogeochemical properties and their interaction with ocean circulation. The $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- record a variety of interesting biogeochemical and mixing processes (Sigman *et al.*, 2000). Of particular interest here, these properties constrain the rates at which vertical mixing and northward advection supply nutrients to shallow waters of the Southern Ocean. This is a critical issue with respect to the role of the Southern Ocean in global change. The $\delta^{18}O$ of O_2 is a nonlinear tracer that reflects the interaction of mixing and respiration in the oceans in a unique way (Bender, 1990; Maier-Reimer, 1993). The triple isotope composition of dissolved O_2 reflects the fraction of dissolved O_2 derived from photosynthesis. This property constrains rates of primary production, and provides a tracer of water mixed from the euphotic zone into mode waters and the thermocline (Luz and Barkan, 2000).

Heavy noble gases are undersaturated in deep ocean waters. Undersaturation comes about because gas exchange lags cooling in deep water formation regions. Observing the evolution of undersaturation is one measure of changes in the nature of intermediate and deep water formation as the oceans warm.

We recommend that such emerging tracers be measured wherever they can make a unique contribution to our understanding of the evolving distribution of bioactive tracers, mixing, and ventilation in the ocean.

4.3.5 Repeat time of ocean sections

We recommend a repeat time of 10 years. Future projections suggest that anthropogenic CO_2 in the oceans will increase by about 20–25% over the next decade. The rise in anthropogenic CO_2 in thermocline waters during this period is expected to be approximately 5 μmol/kg. With currently achieved precision and accuracy (about ± 1 μmol/kg), such an increase can be detected in individual samples and averaged in large data sets. Therefore inventory increases will be accurately constrained. Decadal surveys will reveal changes in ocean ventilation and biological production in the era of global warming, and will document changes in CO_2 sequestration that herald changes in the rate of atmospheric CO_2 increase. Decadal surveys will also constrain ocean O_2

inventories, allowing independent calculations of ocean and land biosphere CO_2 uptake from atmospheric O_2/N_2 studies. We can compare CO_2 invasion into individual basins estimated from global atmospheric data, regional air-sea fluxes of CO_2, and regional ocean inventory changes. In summary, timely updates of the CO_2 distribution in the ocean interior are essential to the evolving comprehensive analysis of the CO_2 balance. However, the ocean interior is unlike other realms in that it cannot be monitored continuously in a comprehensive manner. We believe that decadal updates are the minimal requirement for a "real-time" understanding of evolution of the carbon cycle. Finally, the repeat transects offer excellent opportunities to measure a wide range of ocean properties with great potential for process information, including chlorophyll, pigments, iron, etc. These ancillary measurements will provide critical information for prognostic modeling and interpolation.

4.3.6 Spatial resolution of ocean sections

Our network design study suggests that approximately 2 to 4 meridional and 2 or 3 zonal sections per ocean basin are required to constrain the distribution of anthropogenic CO_2 (see also Taft *et al.*, 1995; Gould and Toole, 1999). Meridional sections are important for understanding variations in basin-scale circulation patterns and anthropogenic CO_2 inventory changes. In the North Atlantic in particular, these should be weighted toward the western portion of the basin, because present knowledge of transport processes suggests that the maximum change in the anthropogenic CO_2 inventory will be found here. However, given our present incomplete knowledge of thermocline ventilation in the Pacific and Indian Oceans, we require additional lines in the central and eastern basins of these oceans as well. Repeat occupation of zonal sections allows the determination of zonal variations in anthropogenic CO_2 inventories, as well as the detection of changes in the rates, pathways, and properties of deep and intermediate waters carried toward the equator from the high latitudes. Zonal sections allow us to calculate transport (fluxes) of water and carbon required to balance the carbon budget within each basin. To satisfy inverse modeling requirements (Wunsch, 1996) for closing carbon budgets on a regional basis, all zonal sections should be coast-to-coast sections located downstream of the thermocline ventilation zones and the deep and intermediate water formation regions. Model results suggest that the region of maximum oceanic uptake of anthropogenic CO_2 is near 40°S–60°S in all oceans. Time series of zonal lines just equatorward of this latitude range are particularly necessary.

High-resolution hydrographic surveys currently offer the only direct method for estimating ocean transport of CO_2. Geostrophic currents are determined from the observed density field, often utilizing an inverse box model to estimate unknown reference level velocities. The net CO_2 transport is the integrated product of the distribution of the currents and CO_2 concentrations. Previous estimates of natural and anthropogenic CO_2 transport (Brewer *et al.*, 1979; Martel and Wunsch 1993; Holfort *et al.*, 1998) reveal that accurate estimates require sufficient spatial sampling of physical properties to resolve the mesoscale eddy field. While the CTD sampling must be sufficient to resolve the eddy variations (~55 km) for transport calculations, regression and interpolation analysis has demonstrated that we can accurately reconstruct the CO_2 field itself, especially below the seasonal thermocline, from a subsampled distribution of lower resolution (Goyet *et al.*, 1995).

Other countries have already committed to occupy lines in addition to those in Table 4-2 and Fig. 4-4. The British plan to occupy 32°S in the Indian Ocean, 45°S in the Atlantic and the northern hemisphere portion of 20°W; the Japanese will occupy 144°E and 165°E in the North Pacific, and 32°S in the South Atlantic and South Pacific; the Germans will occupy 48°N in the North Atlantic; and the Canadians will repeat a line through the subpolar gyre of the North Atlantic from Labrador via Greenland to Scotland, and line P in the northeastern Pacific. Additional lines in the northeastern Atlantic are planned by several countries, while the Australians will occupy a series of sections in the southwest Pacific and southeast Indian Oceans. Finally, the sections south of South America, Africa, and Australia across the Antarctic Circumpolar Current are visited frequently by ships serving the Antarctic bases; it seems likely that most of these sections will be reoccupied on a relatively frequent basis. Thus, the global coverage will likely be considerably more than shown in Fig. 4-4.

When possible, the occupations of these sections should be coordinated to reduce ambiguities in combined interpretation of estimates of inventory increases and lateral transport. For instance, one strategy, based partly on the premise that meridional sections are better for constraining inventories and zonal sections better for constraining transport, would allow best closure of ocean carbon budgets on a basin scale, assuming a 10-year repeat cycle. For each hemisphere of each ocean, meridional sections for inventory estimates should be occupied as closely as possible in time. Then, 5 years later zonal sections for lateral ocean carbon transport estimates should be taken, followed by a reoccupation of the meridional sections 5 years later. In this manner, the meridional sections yield a change in carbon inventory centered over a time interval that appropriately matches the carbon transport estimates derived from the zonal transects. In addition, the staggered occupation of meridional and zonal sections would improve temporal resolution where the zonal and meridional sections cross, likely for the most part in the subtropics.

4.3.7 Time-series observations of the properties of the ocean interior

Ocean interior concentrations of biogeochemical properties and transient tracers vary in response to changes in ventilation and biological activity on a wide range of timescales. Examples of interannual to decadal variations include the response of the ocean to El Niño events, the Pacific Decadal Oscillation, and the North Atlantic Oscillation. We recommend time-series observations at selected sites to observe and document such variability on timescales up to decades (Table 4-3 and Fig. 4-5). These time-series stations will provide the time continuity now lacking in the decadal surveys and will

Table 4-3: Proposed time-series stations as part of this program.

Location	Motivation	Activity	Priority
S/BATS/BTM, Bermuda/U.S.	NAO, Bermuda testbed mooring	Add autonomous instrumentation to ongoing time-series activity	1A
HOT, Hawaii, U.S.	PDO, ENSO, testbed mooring	Add autonomous instrumentation to ongoing time-series activity	1A
Eq. Pacific, especially 0°, 155°W; 2°S, 170°W, U.S.	ENSO variability, testbed mooring	Add autonomous instrumentation to TAO moorings	1A
Station Papa, NE Pacific/Canada	PDO	Add autonomous sampling platform	1B
Bravo, Labrador Sea/Canada	NAO, subarctic response	Add autonomous sampling platform	1B
Mike, Norwegian Sea/Norway	NAO, subarctic response	Add autonomous sampling platform	1B
Pacific sector of the Southern Ocean	Global warming, Antarctic Circumpolar Wave, ENSO connection	Add autonomous sampling platform	2A
Atlantic sector of the Southern Ocean	Global warming, Antarctic Circumpolar Wave, THC changes	Add autonomous sampling platform	2A
Western and eastern equatorial Pacific	ENSO	Add autonomous instrumentation to TAO mooring	2B
Eastern equatorial North Atlantic (Pirata Moorings)	Tropical Atlantic Dipole	Add autonomous instrumentation to Pirata mooring	2B
Western and eastern subtropical South Pacific	Southern Hemisphere subtropical gyre, extremely low Fe environment	Add mooring	2B
Western and eastern subtropical South Atlantic	Southern Hemisphere subtropical gyre	Add mooring	2B

1A = 1st priority, first 5-year period; 1B = 2nd priority, first 5-year period; 2A = 1st priority, 2nd 5-year period; 2B = 2nd or 3rd priority, second 5-year period.

allow the program to detect changes in the oceanic system as they occur. The proposed observation program must be designed to detect such changes early, allowing response with additional observational assets, surveys, and in-depth process studies.

These time-series observations, by extending from the surface ocean into the ocean interior, will also serve as "nodal points" linking the surface variations observed by the large-scale surface program and the large-scale ocean interior changes observed by deep hydrographic surveys. Such a linkage is crucial, since observation programs focused on physical oceanography have shown that a significant fraction of variability associated with decadal timescale changes occurs within the thermocline and can manifest itself back at the surface many years later. For example, Gu and Philander (1996) demonstrated that temperature anomalies can get subducted into the thermocline of the subtropical gyres and resurface back in the tropical Pacific more than a decade later, significantly influencing heat exchange. Furthermore, long-term changes are often more strongly manifested in subsurface

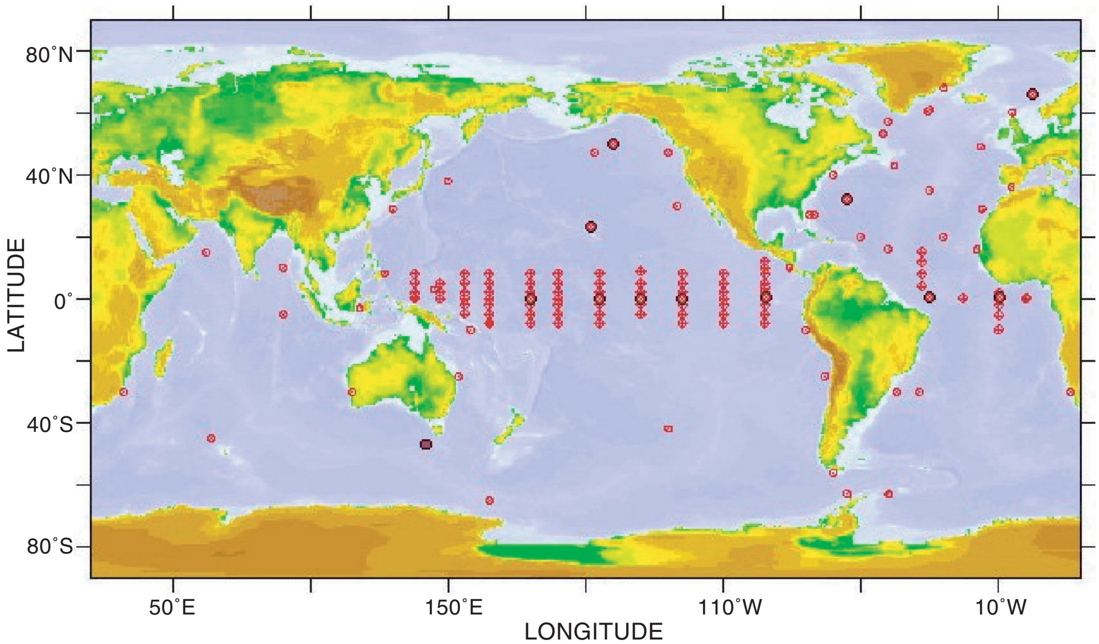

Figure 4-5: World map of existing and proposed mooring sites for long-term interdisciplinary observations. The black open circles show high-priority time-series mooring sites for the Carbon Cycle Science Program.

waters, because the large-scale transport and mixing act as low-pass filters (Deser *et al.*, 1996). By covering timescales from days to decades, these time-series observations will give crucial insight into the mechanisms that govern oceanic variability, insight that will improve assessments of future changes.

4.3.8 Sites for time series station

As in the case of surface measurements (Chapter 3), we recommend, for the first 5-year period, continued support and augmentation to include autonomous platforms and instruments for the two current American time series at Bermuda (BATS) and Hawaii (HOT) for the interior ocean time-series measurements (Table 4-3). We also recommend that a program be formalized for the equatorial Pacific based on the existing TAO mooring array and the ship servicing these moorings (Fig. 4-5).

The data for these three sites will provide critical information on changes in the composition of the interior ocean waters due to circulation and ecosystem changes resulting from ENSO and extratropical climate variability, such as the Pacific Decadal Oscillation and the North Atlantic Oscillation. In addition, for the first 5-year period, we recommend that existing time-series sites in critical high-latitude regions of the North Atlantic and North Pacific be augmented with CO_2 measurements. For the North Pacific, we recommend continuation and augmentation of the Canadian JGOFS time series at station Papa to document the influence of the Pacific Decadal Oscillation. In particular, this study will show how the recently observed change in thermocline oxygen concentrations will evolve, and how they are connected with variations in carbon storage. Because this station is regularly serviced by research ships from Canada, optimal synergisms with ship-based observations can be exploited. We also recommend support and encouragement for interaction with the Japanese time-series studies in the northwestern Pacific. In the North Atlantic, we recommend continuation and augmentation of the Labrador Sea time-series site Bravo and of the Norwegian Sea time-series site Mike, where previous studies revealed large seasonal variations (e.g., Takahashi *et al.*, 1993). These sites are optimally placed to study the impact of the North Atlantic Oscillation on upper ocean and thermocline variability in physics, chemistry, and biology.

For the second 5-year period, when autonomous technology will become fully operational, we recommend extending the existing set of time-series stations into the Southern Ocean, where model simulations clearly indicate that long-term changes in response to global climate change will be most strongly manifested. Extending the observational capabilities into this sensitive area is extremely important because relatively small changes in thermohaline circulation and biogeochemistry can result in large regional changes in CO_2 fluxes and ocean storage. Also, for the second 5-year period, we recommend the addition of time-series stations in the tropical and subtropical South Atlantic and South Pacific. We envision that several of these new time-series sites will be maintained by our international collaborators and will only require specific augmentation with autonomous sensors.

Time-series measurements at fixed stations are currently conducted in two ways: (1) ship-based measurements at intervals of a month (occasionally a bit more frequently) and (2) autonomous sampling from moorings. To understand the long-term changes in the oceanic carbon cycle due to climate change, oceanographers have depended heavily on time-series ship-based data at a very limited number of specific locations in the major oceanic provinces. These have yielded important data sets referred to earlier.

Ship-based time-series measurements are impractical for measuring variability over intervals from a week to a month; they cannot be made during storms or high-sea conditions; and they are too expensive for remote locations. Instrumental advances over the past 15 years have led to autonomous moorings capable of sampling properties of chemical, biological, and physical interest with resolution as good as a minute and a duty cycle of a year or more (e.g., Dickey, 1991; Chavez *et al.*, 1999; Dickey and Falkowski, 2001). This work has provided a growing body of evidence that episodic phenomena are extremely important causes of variability in CO_2 and related biogeochemical properties and processes. We therefore recommend that the new time-series observation sites be focused on autonomous sampling technology with ship-based support as required.

Because one of the problems in defining the spatial and temporal variability of carbon uptake in the ocean interior is lack of data, strategies are needed to increase spatial coverage and sampling frequency at reduced per datum cost. Particular emphasis should be placed on the development of new technology, particularly instruments for measuring CO_2 and related properties on research ships, moorings, profiling floats, and gliders (Goyet *et* *al.*, 1992; DeGrandpre *et al.*, 1995; Friederich *et al.*, 1995; Tokar and Dickey, 2000; Varney, 2000). It is recommended that a portion of this program should be devoted to the development of new automated systems that can be interchangeably mounted on moorings and profiling floats, or used as autonomous systems on volunteer observing ships. For example, the proposed distribution of PALACE and ARGO floats in the Atlantic and Pacific under the CLIVAR program could serve as the primary vehicles for the CO_2 sensors (Davis *et al.*, 2000). A combination of surface drifters and CO_2 sensors on profiling floats and gliders could allow us to observe and quantify the coupled evolution of near-surface and mid-water carbon fields. Recent technological advances in methodology for in situ carbon measurements could make this a reality. For example, the recent development of high-precision in situ methods for TCO_2, TA, and pCO_2 by Robert Byrne and colleagues at the University of South Florida use a compact spectrophotometric analysis system (SEAS; Byrne *et al.*, 2001). The system is capable of spectral analysis from 400 to 750 nm in both absorbance and fluorescence modes. The sample cell is configured to use long pathlength liquid core waveguides (10 to 500 cm) for pH, pCO_2, TCO_2, and TA. The system is deployed with the Bottom Stationed Ocean Profiler (BSOP) or other similar profilers. These devices have been designed to carry SEAS sensors and other instruments, and telemeter chemical and physical data after each cycle. As discussed in Chapter 3, a strong program of autonomous CO_2 sensor and related instrument and platform development and field testing is needed during the first 5-year period of the program. Thus, we strongly endorse the similar recommendations in Chapter 3.

While some CO_2 sensors have been deployed or are ready for deployment on moorings and profiling floats (DeGrandpre *et al.*, 1995), other sensors need further testing under field conditions before they can be considered fully operational (Byrne *et al.*, 2001). The time-series sites provide an excellent opportunity for calibration and field testing during site reoccupations by the surface ship, when the in situ measurements can be compared with shipboard measurements.

4.3.9 Properties to be analyzed at time-series sites

Autonomous observations should focus on characterizing dissolved bioactive constituents and biogeochemical processes in the upper ocean and the thermocline. Properties of particular interest to the CO_2 problem include TCO_2, TA, pCO_2, nutrients, O_2, DOC/DON, particulate organic and inorganic carbon, halocarbons, bio-optical parameters, and bioactive trace metals such as iron. Of these, TCO_2, TA, pCO_2, nutrients, O_2 and halocarbons are directly relevant for determining the distribution of CO_2. POC/PIC and trace metal concentrations are of great interest to process studies of the ocean carbon cycle. Many of these properties can be measured using a combination of in situ analyzers and moored samplers. Observing platforms could be moorings, profiling floats, or even gliders. At the present time, the technology is evolving rapidly, and we make no specific recommendations about sensors, samplers, and platforms. However, the autonomous units must certainly

Table 4-4: Priorities and cost estimates for the interior ocean program.

Element of the implementation plan	Priority	Ship time* ($/year)	Science ($/year)
First 5-Year Period			
Meridional and Zonal Sections (Atlantic and Pacific Oceans)	1	$2,000,000	$2,100,000
Augmenting HOT, BATS, and Equatorial Pacific with autonomous sensors	1	$500,000	$1,500,000
Augmenting high-latitude time-series sites with CO_2 measurements	2	$500,000	$1,100,000
Develop/improve sensors for measurements of two CO_2 system properties	2		$500,000
Second 5-Year Period			
Meridional and Zonal Sections (Southern Oceans)	1	$1,500,000	$2,200,000
Meridional and Zonal Sections (Atlantic, Pacific, and Indian Oceans)	1	$1,500,000	$1,500,000
Augmenting Southern Ocean time-series sites with autonomous sensors	1	$500,000	$1,500,000
Instrumented profiling floats and gliders	2	$800,000	$1,500,000
Augmenting tropical and subtropical time-series sites with autonomous sensors	3	$500,000	$1,500,000

*Ship-time costs are estimated at $20,000 per day.

fulfill two requirements. First, they must be efficient in the sense that they need to operate for long periods of time at the required level of *accuracy and precision*. Second, the analytical uncertainty needs to be smaller than the likely amplitude of interannual timescale variations. The required accuracy depends on the site, resolution attained, and precise objectives. As a guide, accuracy and precision should be about ± 1 μmol/kg for O_2, ± 2 μmol/kg for TCO_2 and TA, and ± 0.2 μmol/kg or $\pm 1\%$ for nutrients (whichever is smaller). As was the case with the WOCE/JGOFS global survey, we recommend continued support for a strong standards and intercalibration effort as a necessary component throughout the duration of the program.

4.3.10 Priorities for the ocean interior

Monitoring the evolving fossil CO_2 inventory is an essential long-term component of any effort to understand oceanic CO_2 exchange. We recommend an integrated approach involving a network of repeat sections and time-series stations using ships, moorings, profiling floats, and gliders to document the continuing large-scale evolution of these fields. This activity would be an ongoing effort and could exploit strong linkages with other efforts such as the transport studies and CLIVAR (Climate Variability and Predictability program) within GOOS (Global Ocean Observing System) and GCOS (Global Climate Observing System) to make efficient use of ship time. This ongoing ocean interior component of the Carbon Cycle Science Program will consist of three major research activities phased over two 5-year periods (Table 4-4).

4.3.11 The first 5 years

- **Conduct meridional and zonal sections in the Atlantic and Pacific (priority 1).** Several of the Atlantic and Pacific transects were occupied more than 7 years ago, and can provide valuable data quickly.

- **Augmentation of existing U.S. time-series sites in the North Atlantic, North Pacific, and equatorial Pacific with autonomous sensors (priority 1).** We strongly recommend that autonomous time-series measurements be tested and "proven" at these sites before they are deployed in large numbers. This means that the instruments have repeatedly demonstrated their ability to maintain the required levels of precision and accuracy for the planned duration of the deployments.

- **Augmentation of high latitude time series sites with CO_2 measurements (priority 2).** We recommend that existing time-series sites in critical high-latitude regions of the North Atlantic and North Pacific be augmented with CO_2 measurements.

- **Development of new instrumentation for two CO_2 parameters and CO_2-related species on moorings, profiling floats and gliders (priority 2).** We recommend that systems that measure at least two components of the carbon system simultaneously be given high priority for development.

4.3.12 The second 5 years

- **Expansion of the global surveys to the Southern Ocean (priority 1).**

- **Implementation of meriodional and zonal sections in the Pacific, Atlantic and Indian Oceans (priority 1).**

- **Expansion of the time-series stations in the Southern Ocean (priority 1).**

- **Deployment of instrumented profiling floats and gliders (priority 2).**

- **Expansion of the time-series stations in the tropical and subtropical regions of the South Atlantic and South Pacific (priority 3).**

It is assumed that the program resources will grow over the 10-year period to support these enhanced research activities. It is also envisioned that the field and modeling program will continue beyond the 10-year effort described here. This implementation plan concentrates on the first 10 years of the program. Future implementation plans will be developed as needed as the program evolves over the next decade.

4.4 Summary

The Ocean Interior Program consists of repeated and nearly continuous systematic full water column sampling of CO_2 and CO_2-related parameters, tracers, and hydrography to determine the large-scale decadal evolution of the anthropogenic CO_2 inventory in the oceans. It will provide necessary data required to improve global circulation and biogeochemistry models on global and basin scales, close the decadal basin-scale budget of carbon using information on the basis of inventory changes and lateral transport, and determine the response of the oceanic carbon system to interannual and interdecadal climate variability. Our strategy is to put in place a global ocean-observing network of sampling platforms to make observations, including repeat ship-based sections, and time-series stations using moorings, profiling floats, and navigated gliders. This approach documents the continuing evolution of these fields and provides a powerful constraint for model parameterizations of the carbon system in the oceans.